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Additive Manufacturing of Titanium Alloys: Microstructure and Properties

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Abstract

Additive manufacturing technology provides a novel approach for the rapid fabrication of complex titanium alloy components, demonstrating significant advantages in fields such as aerospace and biomedical engineering. However, the unique non-equilibrium solidification and layer-by-layer thermal cycling inherent to additive manufacturing lead to the formation of distinctive microstructures within titanium alloys, accompanied by residual stresses, gas porosity, and lack-of-fusion defects. These features consequently affect the mechanical anisotropy and service reliability of the components. This review systematically summarizes the microstructural evolution mechanisms, defect formation mechanisms, and their effects on tensile and fatigue properties of titanium alloys (primarily Ti-6Al-4V) fabricated by three typical additive manufacturing processes: laser powder bed fusion, laser directed energy deposition, and electron beam powder bed fusion. The analysis focuses on the regulatory effects of process parameters (laser power, scanning strategy, substrate preheating) on α/β phase morphology, grain texture, and residual stress. Furthermore, the efficacy of post-processing techniques, including hot isostatic pressing and heat treatment, on microstructural homogenization and property enhancement is discussed. Finally, addressing challenges such as large-scale component manufacturing, multi-material interface control, and the design of alloys specifically for additive manufacturing, this review provides an outlook on future directions involving integrated computational materials engineering and intelligent process control. This review aims to provide a theoretical basis for process optimization and property prediction of additively manufactured titanium alloys.

Keywords: *additive manufacturing; titanium alloys; microstructure; mechanical properties; hot isostatic pressing (HIP); anisotropy*

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I. INTRODUCTION

Titanium alloys, owing to their excellent specific strength, corrosion resistance, high-temperature performance, and biocompatibility, have become critical structural materials in aerospace, marine engineering, biomedical, and automotive industries. Among them, Ti-6Al-4V (TC4) is the most widely used, accounting for more than 50% of the total titanium alloy production. In the aerospace sector, titanium alloys are employed in the manufacture of engine fan blades, compressor disks, and airframe bulkheads. In the biomedical field, due to their non-magnetic nature, low elastic modulus (relative to stainless steel and cobalt-chromium alloys), and favorable osseointegration capability, titanium alloys are extensively used for artificial joints, spinal fixation systems, and dental implants [1]. However, the high melting point (approximately 1600–1650°C), low thermal conductivity (approximately 6–7 W/m·K), and high chemical reactivity of titanium alloys pose significant challenges in conventional processing.

Conventional casting and forging processes exhibit notable limitations when processing titanium alloys. Although casting can produce complex shapes, it is prone to shrinkage porosity, segregation, and coarse grain formation, accompanied by severe surface oxidation, necessitating subsequent hot isostatic pressing and heat treatment to improve properties. Forging achieves excellent mechanical properties but is limited by tooling and machining constraints, making it difficult to fabricate features such as thin walls, deep cavities, and internal channels. Moreover, the material utilization rate is typically below 30%, with machining allowance sometimes reaching up to 90% [2]. For expensive titanium alloys, this low material utilization not only significantly increases manufacturing costs but also prolongs production cycles. Therefore, developing a processing technology that combines complex shape formability with high material efficiency has become an urgent need.

Additive Manufacturing (AM), based on the principle of "discrete-stacking," directly fabricates three-dimensional parts from CAD models in a layer-by-layer melting/solidification manner. This technology overcomes the geometric constraints of traditional subtractive manufacturing, enabling the production of titanium alloy components with internal lattice structures, conformal cooling channels, and topology-optimized geometries, while increasing material utilization to over 80% and substantially shortening the development and manufacturing cycles [3]. Currently, the additive manufacturing technologies applied to titanium alloys mainly include three categories: Laser Powder Bed Fusion (LPBF), Laser Directed Energy Deposition (LDED), and Electron Beam Powder Bed Fusion (EB-PBF). LPBF, with its high precision (dimensional error < 0.1 mm) and excellent surface quality, is suitable for manufacturing fine-featured structures. LDED features a high deposition rate (up to 1–4 kg/h) and an open processing environment, making it suitable for large-scale components and repair applications. EB-PBF operates in a vacuum with substrate preheating that substantially reduces residual stress, making it suitable for crack-prone alloys [4].

Although additive manufacturing overcomes the geometric limitations of conventional processes, its inherent "rapid melting – rapid solidification – layer-by-layer thermal cycling" process subjects titanium alloys to extreme non-equilibrium phase transformations and complex thermal histories, resulting in microstructures fundamentally different from those of conventionally processed counterparts. Specifically: LPBF exhibits a cooling rate as high as 10^5–10^6 K/s, where the $\beta \rightarrow \alpha'$ martensitic shear transformation dominates, forming fine acicular α' martensite accompanied by extremely high residual stress. LDED has a relatively lower cooling rate (10^2–10^4 K/s), and multiple thermal cycles induce an "intrinsic heat treatment effect", readily forming coarse, penetrating columnar β grains and mixed α+β microstructures within grains. EB-PBF, owing to a preheating temperature of 650–1100°C, significantly reduces the cooling rate, and the microstructure is dominated by α+β lamellae (Widmanstätten or basket-weave), with martensite rarely observed [5–7]. Furthermore, defects such as gas porosity, lack-of-fusion, residual stress, and even cracks are common in additively manufactured titanium alloys. These defects, together with anisotropic columnar grain textures, lead to pronounced anisotropy in mechanical properties (especially fatigue performance) and values much lower than those of wrought counterparts, severely limiting their application in safety-critical components (e.g., aircraft structural parts, long-term load-bearing implants).

To address these issues, extensive research has been conducted on process parameter optimization, scanning strategy design, substrate preheating, post-processing (heat treatment, hot isostatic pressing), and in-situ monitoring with feedback control, aiming to tailor the microstructure, eliminate defects, reduce anisotropy, and enhance overall mechanical properties. In recent years, Hot Isostatic Pressing (HIP) has been recognized as the most effective method for eliminating internal gas porosity and lack-of-fusion defects. After HIP treatment, the fatigue performance of additively manufactured titanium alloys can approach or even reach the level of wrought products [8]. Meanwhile, Integrated Computational Materials Engineering (ICME) approaches, based on phase-field simulations and crystal plasticity finite element methods, are accelerating the quantitative understanding and prediction of process–microstructure–property relationships.

This review, from the perspective of process–microstructure–property linkages, systematically summarizes the microstructure evolution mechanisms, typical defect formation mechanisms, and their effects on tensile and fatigue properties of titanium alloys (mainly Ti-6Al-4V) fabricated by the three mainstream additive manufacturing technologies: LPBF, LDED, and EB-PBF. The analysis focuses on the regulatory effects of process parameters (laser power, scanning speed, scanning strategy, layer thickness, substrate preheating) on α/β phase morphology, grain morphology, crystallographic texture, and residual stress. Furthermore, the effectiveness of post-processing techniques, including heat treatment and hot isostatic pressing, on microstructural homogenization, defect healing, and mechanical property enhancement is discussed. Finally, current challenges (e.g., large-scale component manufacturing, multi-material interface control, insufficient development of alloys specifically designed for additive manufacturing) are summarized, and future directions such as integrated computational materials engineering, intelligent process control, and the development of novel additive manufacturing titanium alloys are proposed. This review aims to provide a systematic theoretical reference for process optimization, microstructure prediction, and service performance evaluation of additively manufactured titanium alloys.

II. Result And Discussion

1. Laser Powder Bed Fusion (LPBF)

LPBF employs a high-energy laser beam (typically a fiber laser with a wavelength of approximately 1070 nm) to selectively melt pre-laid titanium alloy powder layers, with a layer thickness of 20–60 μm and a spot diameter of approximately 50–100 μm. The cooling rate is extremely high, reaching 10^5–10^6 K/s, far exceeding that of conventional ingot cooling (~10^2 K/s). This extreme non-equilibrium solidification leads to a dominant $\beta \rightarrow \alpha'$ martensitic transformation, while the steep temperature gradient at the top of the melt pool promotes the epitaxial growth of columnar β grains along the building direction [9]. The advantages of LPBF lie in its high precision (dimensional error < 0.1 mm) and capability to form complex fine features, but high residual stresses readily cause part distortion or cracking.

2. Laser Directed Energy Deposition (LDED)

LDED uses a coaxial powder feeding method to form a melt pool on the substrate or previously deposited layer, with a layer thickness of 0.5–2 mm and a spot size of 1–3 mm. The cooling rate is relatively lower (10^2–10^4 K/s), and the heat accumulation effect is significant. During multi-layer deposition, the previously deposited layers repeatedly undergo thermal cycling, inducing an "intrinsic heat treatment" effect in the subsurface regions: partial decomposition of martensite into α+β, or coarsening of lamellar α [10]. LDED is suitable for the fabrication of large-scale components and the repair of damaged parts, but the as-built surface is rough, and coarse columnar β grains spanning multiple deposited layers cause significant mechanical anisotropy.

3. Electron Beam Powder Bed Fusion (EB-PBF)

EB-PBF operates in a vacuum, where the electron beam is deflected by electromagnetic coils for scanning, allowing preheating of the powder bed (typically to 650–1100°C). Preheating substantially reduces the temperature gradient and cooling rate (approximately 10^3–10^4 K/s), significantly mitigating residual stress; therefore, EB-PBF parts hardly experience cracking. Because the cooling rate is below the critical value for martensite formation, the microstructure of EB-PBF titanium alloys typically consists of fine α+β lamellae (Widmanstätten or basket-weave structure) rather than martensite [11]. However, the vacuum system prolongs the process cycle, and the surface accuracy is lower than that of LPBF.

4. Phase Composition and Morphology

In Ti-6Al-4V, the equilibrium microstructure is α (hexagonal, HCP) + β (body-centered cubic, BCC). The non-equilibrium conditions of additive manufacturing alter the phase transformation pathways:

LPBF: The extremely high cooling rate leads to a β→α′ martensitic shear transformation. α′ appears as acicular or lath-shaped, with a high density of internal dislocations and no precipitation of the β phase. In some regions, small amounts of residual β or α+β eutectoid can be observed [12].

LDED: The moderate cooling rate and repeated thermal cycling result in a complex microstructure. The as-deposited condition typically contains prior columnar β grains, within which acicular α′ martensite or α+β lamellae are present, and microstructural coarsening in the heat-affected zone occurs near the fusion line [13].

EB-PBF: Under preheating and a relatively low cooling rate, the β→α diffusional transformation dominates, forming a lamellar structure of α laths alternating with β phases (interlamellar spacing approximately 0.5–2 μm), with no martensite.

5. Grain Morphology and Texture

A hallmark feature of additively manufactured titanium alloys is the epitaxial growth of columnar β grains along the building direction. This occurs because heat flow is primarily vertical (from the bottom to the top of the melt pool), and competitive grain growth leads to a preferred orientation of <001> or <111>. In LPBF, the width of columnar β grains is typically 50–200 μm, and they can span dozens of deposited layers. In LDED, the columnar grains are even coarser (width up to the millimeter scale). In EB-PBF, due to preheating altering the heat flow conditions, the columnar grain feature is weakened, and even equiaxed grain structures can be obtained [14].

The strong crystallographic texture gives rise to mechanical anisotropy: when loaded parallel to the building direction (longitudinal direction), the Schmid factors differ, resulting in variations in yield strength and elongation compared with the transverse direction.

6. Typical Defects

Gas porosity: Mainly caused by hollow powder particles or gas entrapment, mostly spherical with a size <100 μm. It can be reduced by process parameter optimization (e.g., laser power, scanning speed).

Lack of fusion (LOF): Caused by insufficient energy input or uneven powder spreading, exhibiting an irregular shape and being extremely detrimental to fatigue performance. Increasing laser power or adopting a remelting scanning strategy can significantly reduce LOF defects.

Residual stress: Arising from constrained thermal contraction due to high temperature gradients. Residual stress in LPBF can approach the yield strength of the material, leading to part distortion or cracking. Substrate preheating, scanning strategy optimization (e.g., island scanning, zigzag scanning), and subsequent stress-relief annealing are common mitigation methods [15].

Cracks: Less common in titanium alloys, but solidification cracks or liquation cracks may appear in specific alloys with high concentrations of Al and V or at the junctions of large-thickness sections.

7. Heat Treatment and Hot Isostatic Pressing

Heat treatment: Sub-β-transus annealing (e.g., 800°C/2h) of LPBF parts promotes the decomposition of α′ martensite into α+β, significantly increasing elongation (up to 12%–15%) while moderately decreasing strength (to 1000–1100 MPa). Solution and aging treatment can be performed in the α+β or β single-phase region to control α lath thickness and β phase volume fraction [16].

Hot Isostatic Pressing (HIP): Conducted at elevated temperatures (900–1000°C) and high pressures (~100 MPa), HIP can close internal gas porosity and lack-of-fusion defects while promoting microstructural homogenization. After HIP, additively manufactured titanium alloys can achieve fatigue performance meeting or even exceeding that of wrought products. Currently, HIP has been adopted as a standard post-processing step for critical additively manufactured titanium alloy parts in the aerospace industry[17].

III. CONCLUSION

In summary, the three typical additive manufacturing processes—Laser Powder Bed Fusion, Laser Directed Energy Deposition, and Electron Beam Powder Bed Fusion—produce distinctly different microstructures and defect distributions in titanium alloys due to significant differences in their thermal history characteristics. LPBF, characterized by martensitic transformation under extremely high cooling rates and high residual stress, is suitable for high-precision complex components but requires strict control of cracking risks. LDED, owing to heat accumulation and repeated thermal cycling, forms coarse columnar grains and mixed microstructures, making it suitable for large-scale components and repair, albeit with pronounced anisotropy. EB-PBF, benefiting from preheating, achieves low residual stress, an α+β lamellar microstructure, and weak anisotropy, but at the cost of a longer process cycle. The three processes exhibit systematic differences in phase composition (α′ martensite vs. α+β lamellae), grain morphology (columnar vs. equiaxed), and defect types (gas porosity, lack of fusion, residual stress), which directly lead to anisotropy in tensile and fatigue properties. Regarding post-processing, sub-β annealing effectively controls α′ decomposition and the α/β ratio, while hot isostatic pressing closes internal defects and significantly enhances fatigue life. The synergistic application of these two post-processing methods enables additively manufactured titanium alloys to achieve comprehensive mechanical properties approaching or even exceeding those of wrought counterparts. This systematic understanding of process–microstructure–property relationships provides a critical theoretical basis for process selection, parameter optimization, and post-processing strategy development for additively manufactured titanium alloys.

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